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GENETICALLY RELATED PULSES GENERATED BY COSMIC RAYS

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/Figures are appended./

Pulses produced by cosmic rays in ionization chambers have generally been assumed to be due to the simultaneous action of a group of relativistic particles, namely, showers. But an analysis of the data of various authors, made by D. V. Skobel'tsyn /1/, shows that at great altitudes the main part of the pulses is to be explained by the action of heavy particles, not showers.

One of the authors of this article with the collaboration of V. I. Veksler and V. A. Khvoles /2/ worked out a method for recording on films the magnitude of pulses originating simultaneously in two groups of proportional counters. This method possesses great possibilities for studying the generation of ionization pulses. A description of experiments by this method will be found below; it not only corroborates Skobel'tsyn's conclusion but also expresses definite considerations as to the properties of particles which generate pulses.

If ionization pulses are assumed to be produced by a great number of relativistic particles, each of which creates only a small share of the pulse, then the magnitudes of the pulses originating under the action of such a shower in two groups of proportional counters placed one over the other should differ very little among themselves. On the contrary, if the pulses are created by a small number of highly ionizing particles, then the magnitudes of the pulses in the two groups of proportional counters will generally differ greatly one from the other.

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This circumstance makes it possible to explain the nature of pulses coinciding in time in two groups of proportional counters. Tests were carried out in the summer and autumn of 1946 at Pamir in the district of Murgab at 3,860 meters. The apparatus was installed in a thin plywood house with a minimum amount of thick material around the counters.

Each of these two groups of proportionl counters consisted of three counters, rectangular in cross section, which were connected in parallel and placed in one common apartment. The counter sizes were as follows: length of working piece, 250 millimeters; width, 60 millimeters; and height, 20 millimeters. The counters were filled with argon dried in a technically accurate manner under a pressure of 740 millimeters of Hg. To eliminate traces of water vapor and oxygen, metallic sodium was placed in one of the outlets of the glass part of the counters. In one part of the experiments, counters with a duraluminum cathode, 2 millimeters thick were used and, in another part, counters with a red copper cathode, one millimeter thick, were used. Inasmuch as no difference at all could be discovered between the results obtained with these two types of counters, we shall not in the future make any distinction between experiments with duraluminum and red copper counters.

The construction of the counters, showing the independence of the gas amplification factor of the place where the particles hit the counter, and tests are minutely described by V. I. Veksler and L. N. Bell [3].

Pressure is supplied separately to all six proportional counters, which makes it possible to set up a uniform gas amplification in all the counters. This is checked by the number of pulses in the "background" of the counter.

The apparatus is graduated by the method used in the work of Bell, Birger, and Veksler [4] and is based upon the determination of the double coincidences observed upon the appearance in each of the counters of ionization corresponding to the probable ionization from relativistic particles. The working sensitivity of the apparatus is selected so that it operates when not less than 700 pairs of ions (simultaneous passage of not less than five relativistic particles) are formed in each group of counters.

The Trost counters used in this work are 400 millimeters long and 38 millimeters in diameter. The cathodes are made of duraluminum 0.3 millimeters thick.

The experiment correlates the magnitudes of the pulses in both groups of proportional counters into two groupings (Figure 1).

Here 1 and 2 are two groups of proportional counters; 3 is a group consisting of 5 Trost counters connected in parallel; 4, 5, and 5 are single Trost counters. Counters 4 and 5 have the same dimensions as each of the counters in group 3 and counter 6 has a working length of 150 millimeters and a diameter of 40 millimeters.

In arrangement I the pulses are recorded on film in both of the proportional counters when there are triple coincidences (1, 2, 3). Thus, the system has a threshold corresponding to five relativistic particles, and pulses of magnitude less than some value a do not appear on the film.

As may be seen from the illustration, the counters are arranged vertically and a layer of aluminum is placed between them. The total amount of matter through which a particle must pass in order to fall from one group of proportional counters to another amounts to about 7 grams per square centimeter.

In arrangement II the pulses are recorded on the film in both groups of proportional counters when there are triple coincidences in Trost counters 4, 5, and 6, arranged on a horizontal plane at a great distance one from the other. Thus, the apparatus records extensive showers and the proportional counters are not involved in selecting coincidences. Consequently, in this case the apparatus does not have a threshold. Magnitudes as small as desired can be recorded on the film. The pressure on the proportional counters and the sensitivity of the radio setup remain the same as in arrangement I.

In arrangement II to operate the apparatus the appearance of extensive showers of at least three particles is necessary. In arrangement I operation of the apparatus can be brought about even by a single particle if it produces sufficient ionization in both counters. The admission capacity of the apparatus is so great that chance triple coincidences are not an important factor.

The absolute number of coincidences recorded in arrangement I amounts to 66 per hour and in arrangement II to 12 per hour. However, if we isolate in arrangement II those pulses whose magnitudes in both counter groups are five times greater than the ionization caused by a relativistic particle, then the number of coincidences in arrangement II will amount to only about 10 percent of the number of coincidences in arrangement I.

The pulse distribution according to magnitude in both groups of proportional counters is represented in Figure 2. Heavy dots and triangles refer to pulses in the upper and lower groups of proportional counters in arrangement I; circles and little crosses refer to the same counters in arrangement II. As may be seen from the illustration, the distribution practically coincides for the upper and lower group, but the results obtained from arrangement I differ sharply from those obtained from arrangement II. This circumstance undoubtedly indicates that the coincidences in arrangement I are produced not by showers composed of relativistic particles but by the formation of secondary particles in both groups of proportional counters.

It may be assumed that in determining the sensitivity of the apparatus some error is probable and that in the operation of the apparatus, pulses also register less than 700 pairs of ions, in which connection the coincidences in arrangement I are then explained by the usual fluctuations in the ionization of relativistic particles. However, the absolute number of coincidences and the comparatively slow decrease in the pulse distribution curve according to magnitude (when the magnitude of the pulses doubles, the number of pulses decrease to one third show with absolute clearness that it is incorrect to explain the origin of the recorded coincidences by fluctuations in ionization. In fact, according to L. Landau's theory [5], the probability of triple coincidences is eight times greater than the probability of sixfold coincidences.

Pulse distribution according to magnitude may be approximated by a formula of the type $f(A)dA = Be^{-\alpha A}dA$, where A is the magnitude of the pulse and f(A) is the number of pulses of magnitude A, with B and α as constants. The curve referring to arrangement I is plotted with $\alpha = 0.50$; the curve for arrangement II with $\alpha = 0.27$.

The correlation between the magnitudes of pulses in both groups of proportional counters is calculated in the following discussion.

The ordinate axis measures the magnitude of pulse A_1 in the upper group of proportional counters, and the abcissa axis measures the magnitude of pulse A_2 in the lower group of proportional counters (Figure 3). Then each pulse (A_1, A_2) will be represented by a point in the quadrant. In the ideal case when complete correlation $(A_1 = A_2)$ occurs, the point is located on a straight line 45 degrees to the coordinate axes. As a matter of fact, however, some scattering of the points will be observed. Let us select the produced angle $2\Delta\phi = 2(\phi - \pi/4)$, symmetrically located relative to the bisector of the quadrant, and let us assume a number of points $2n'$ within this angle for the experiment in question. On the other side, there may be a number of points $2n$, each one of which must fall in the selected angle $2\Delta\phi$, if the magnitudes A_1 and A_2 are independent of each other and hence if there is no correlation between them.

Let us denote by $\Phi(A_1, A_2)$ the distribution function of points in the plane. Then, if A_1 and A_2 are independent, it follows that:

$$\Phi(A_1, A_2)\, dA_1\, dA_2 = f(A_1) f(A_2)\, dA_1\, dA_2$$

or

$$\Phi(A_1 A_2)\, dA_1\, dA_2 = Ce^{-\alpha(A_1 + A_2)}\, dA_1\, dA_2$$

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The constant C is determined from the Normalizing condition:

$$\int_a^\infty\int_a^\infty \Phi(A_1, A_2)\, dA_1\, dA_2 = N$$

where N is the total number of recorded pulses and a is the threshold of sensitivty of the apparatus.

Hence,

$$C = N\alpha^2 e^{2\alpha a}$$

By integrating ρ and ϕ in polar coordinates, we shall find the number of points within the angle $2\Delta\phi$ for the case where there is no correlation between A_1 and A_2:

$$2n(\phi) = 2C\int_{\pi/4}^{\phi} d\phi \int_{a/\cos\phi}^{\infty} e^{-\alpha\rho(\sin\phi + \cos\phi)}\, \rho\, d\rho$$

or

$$2n = 2Ne^{2\alpha a}\int_{\pi/4}^{\phi} \frac{\alpha a(\tan\phi + 1) + 1}{1 + \sin 2\phi}\, e^{-\alpha a(\tan\phi + 1)}\, d\phi$$

The calculation is carried out by expanding the exponential function into a series.

The ratio n'/n measures the correlation of pulse magnitudes in groups 1 and 2 of the proportional counters. The results of the experiment are set forth in Tables 1 and 2. Table 1 refers to the angle $2\Delta\phi = 37$ degrees and Table 2, to the angle $2\Delta\phi = 10$ degrees.

Table 1

$2\Delta\phi = 37^\circ$	N	2n'	2n	n'/n
Arrangement I	384	218	234	0.93
Arrangement II	269	147	90	1.63

Table 2

$2\Delta\phi = 10^\circ$	N	2n'	2n	n'/n
Arrangement I	384	76	66	1.15
Arrangement II	269	54	24	2.25

As is to be expected from the pulse distribution and the above-stated considerations, the correlation of pulses according to magnitude for arrangement II in the selection of showers is much more strongly expressed than for arrangement I. Hence, this data also shows that in a vertical dispositon of counters the majority of the coincidences is produced not by showers but by some other mechanism.

As indicated, the layer between the counters is equivalent to about 7 grams per square centimeter. Consequently a slow proton, with a different ionization sufficient to operate the apparatus, cannot pass from the upper to the lower counter. As alpha particles of such great energy are not observed, the coincidences cannot be assumed to be produced by single strongly ionizing particles. But it is entirely admissible that certain heavy particles simultaneously appear in the upper counter; one of these particles has a path sufficient to pass through the lower counter. After passing through the interlayer, the particle is slowed up and in falling into the lower counter its specific ionization is found to be fivefold or more.

But, from the standpoint of this assumption, the number of coincidences should greatly depend on the thickness of the layer between the counters. We did not carry on detailed research as to this dependence. But qualitative observations made and also experiments conducted by one of the authors and V. I. Veksler [6] show that the number of coincidences is only slightly dependent upon the thickness of the interlayer. Furthermore, from the standpoint of such an explanation, the curve of pulse distribution according to magnitude should be different for the upper and lower groups of counters. Hence, the assumption appears more plausible to us that the coincidences observed in a vertical arrangement of counters are explained by the formation of secondary particles in the upper and lower groups of counters.

A similar conclusion is drawn from observation in another experiment conducted by us at the same altitude and with the same counters. The plan of this experiment is given in Figure 4. Here 1 and 2 are two groups of proportional counters and 3 and 4 are groups of Trost counters. The experiment consists of simultaneously measuring by means of two electromagnetic "numerators" the number of triple coincidences (1, 2, 3) and anticoincidences (1, 2, 3-4) for two different arrangements of group 3 composed of Trost counters.

Arrangement A corresponds to a vertical disposition of all four groups of counters; in arrangement B group 3 is moved out one meter in a horizontal plane.

The sensitivity of the apparatus remains the same as in the previous experiment (the minimum recorded ionization corresponds to the simultaneous fall of about five relativistic particles), but the solid angle formed by the apparatus was somewhat larger.

The results of the measurements are given in Table 3.

Table 3

	Arrangement A	Arrangement B	Ratio A/B
Triple coincidences (1, 2, 3)	109±3.7 per hr	23.8±1.1 per hr	0.22±0.015
Anticoincidences (1,2, 3-4)	12.4±1.2 per hr	0.23±0.13 per hr	0.22±0.01
Relation			
$\frac{(1,\ 2,\ 3\text{-}4)}{(1,\ 2,\ 3)}$ (in %)	11.3±1.5	1.0±0.7	———

As may be seen in the table, moving group 3 counters to a distance of one meter leads to an 80 percent reduction in the number of triple coincidences (1, 2, 3). This means that in arrangement A at least 80 percent of all recorded coincidences cannot be produced by extensive showers. Thus, this data fully confirms the results obtained by the analysis of the pulse distribution according to magnitude and of the correlation of their magnitudes.

To explain the penetrating power of generating particles, an experiment was made in which a 12-centimeter-thick lead filter was alternately placed under the apparatus and removed from under it. Qualitative measurements made show that the majority, at least, of the generating particles pass through 12 centimeters of lead. This circumstance demonstrates once more that the triple coincidences observed cannot be produced by fluctuations in the ionization of relativistic particles. In fact, in this case the number of triple coincidences would be proportional to the total number of relativistic particles passing through the apparatus. Since at this altitude the soft component amounts to 50 percent of the total density of cosmic showers, to place 12 centimeter of lead under the counters, thus eliminating the soft componenet, would halve the number of triple coincidences.

Let us now consider again the question of the anticoincidences observed (1, 2, 3-4). The figures adduced show that in arrangement A in approximately 10 percent of the cases discharges in the two upper and lower compartments are not accompanied by a discharge in the middle compartment of anticoincidences. On the contrary, in arrangement B the comparative share of such cases drops sharply. This circumstance makes it abundantly clear that anticoincidences (1, 2, 3-4) cannot be produced by poor operation of the channel of the anticoincidence amplifier.

It may be assumed that the anticoincidences (1, 2, 3-4) are explained by a chance coincidence of true anticoincidences (1, 3-4) with a pulse in the counters of group 2. With the removal of compartment 3, the number of anticoincidences (1, 3-4) is reduced and hence the number of anticoincidences (1, 2, 3-4) is diminished. But control measurements of the number of identical coincidences show that they amount to not more than 10 percent of the effect observed.

Nevertheless, an experiment was made to get a supplementary control over chance coincidences, in which both compartment 1 and compartment 3 were moved off to the side. Their relative positions are not changed thereby. The number of chance coincidences (1, 2, 3-4) is thereby increased at the expense of the increase in (1, 3-4). Therefore, if anticoincidences (1, 2, 3-4) are produced by chance coincidence, their absolute number must thereby be increased as compared with the number of anticoincidences in arrangement A. But, in fact, on moving the position of compartments 1 and 3, 2.5 anticoincidences (1, 2, 3-4) per hour are observed.

Finally, one more control experiment was carried out in which an additional compartment, compartment 5, with Trost-type counters, similar to compartment 3, was placed under compartment 2. On the one hand, measurements were made alternately of coincidences (1, 2, 3) and anticoincidences (1, 2, 3-4) and, on the other hand, measurements of coincidences (1, 2, 3, 5) and anticoincidences (1, 2, 3, 5-4) were made. The results of this experiment also thus show that chance coincidences are not important factors in (1, 2, 3-4).

Placing even one and 21 millimeters of lead under compartments does not change the number of recorded anticoincidences.

Clearances between the counters in compartment 4, including the walls of the counters themselves, amount to approximately 7 - 8 percent of the area covered by the counters. Hence, the ascertained percentage of anticoincidences likewise shows that they cannot be produced by showers or by groups composed of some charged particles passing through the whole apparatus. Since it is shown above that the effects recorded by us cannot be produced by single strongly ionizing particles, it is likewise established that in cosmic showers genetically related pulses are produced by secondary particles, which are formed in both groups of proportional counters.

The thickness of the effective layer from which the recorded secondary particles are drawn is still not determined. If the effective cross section is assumed to be of the order 10^{-24} square centimeters at the core and the stream of generating ionizing particles is considered to amount to 10 percent of the stream of hard component particles, then in order to explain the observed effect of correlated pulses the thickness of the effective layer must be of the order of magnitude one centimeter of aluminum.

But if the generating particles are considered as nonionizing, then their stream can be assumed at least to approximate the stream of the hard component. Further, it may be assumed that nonionizing particles appear in the groups, at the expense of which there is a corresponding increase in the probability of a simultaneous appearance of secondary particles in both groups of proportional counters. Hence, starting from the hypothesis of the nonionizing nature of generating particles, we can assume a smaller value for the paths of secondary particles and the effective cross section of their formation. Such as assumption seems more probable to us.

The data obtained indicates the assumption that when a pulse develops in one group of counters, then slow secondary particles are formed which produce with great efficiency a pulse in another group of counters.

In conclusion, the authors express their thanks to Academician D. V. Skobel'tsyn, and to Professors V. I. Veksler and V. L. Ginzburg for their valuable discussion of these results.

/Appended figures follow./

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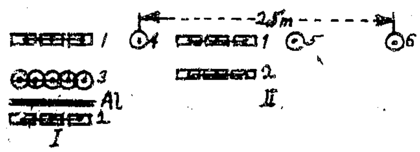

Figure 1.

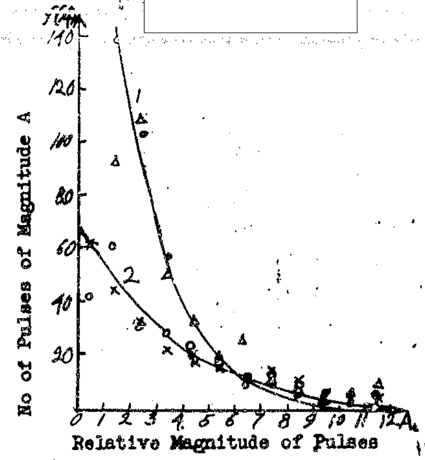

Figure 2.

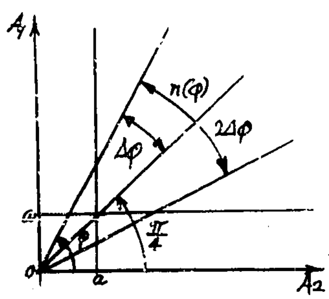

Figure 3.

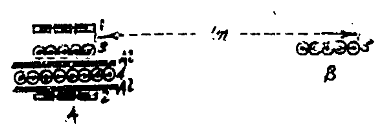

Figure 4.

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